Drought indices relevant to climate change

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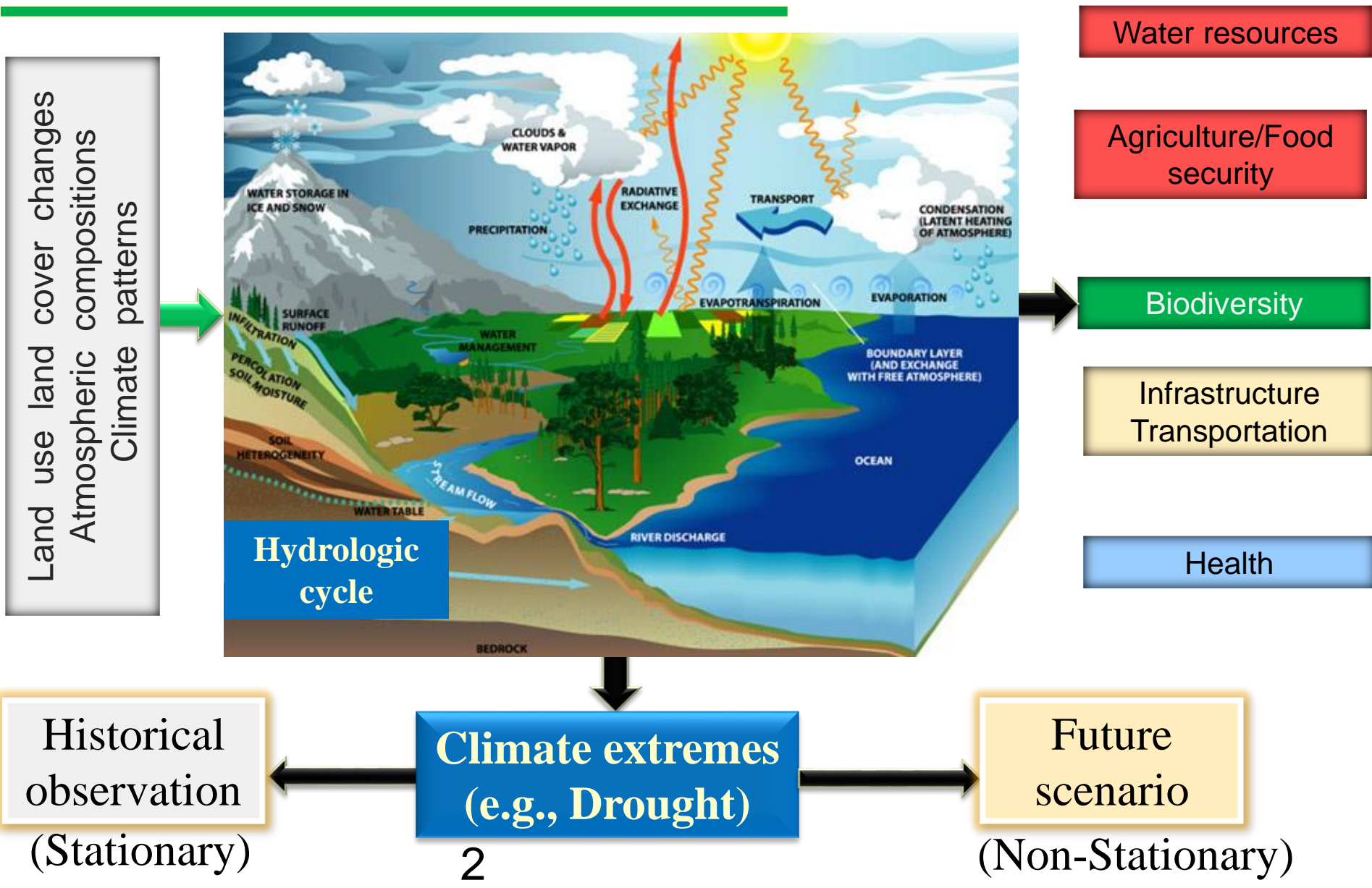Glenn Department of Civil Engineering

Clemson University

Reference:

Mukherjee, S., Mishra, A. K., Trenberth, K. (2018). Climate Change and Drought: a Perspective on Drought Indices, *Current Climate Change Reports*.

Mishra, A. K., and Singh, V. P. (2010), A review of drought concepts, *J Hydrology*

Rationale

Land use land cover changes
Atmospheric compositions
Climate patterns

Hydrologic cycle

Water resources

Agriculture/Food security

Biodiversity

Infrastructure Transportation

Health

Historical observation
(Stationary)

Climate extremes (e.g., Drought)

Future scenario
(Non-Stationary)

Presentation Outline

❖ Drought Overview

❖ Association: Drought Indices & Land Surface Warming

❖ Challenges: Drought Indices for Climate Change Studies

❖ Meaningful Applications of Regional Drought Indices

❖ Summary and Conclusions (Key points)

Drought Overview

Global Drought Issues

- Anthropogenic warming has increased drought risk in California *(PNAS, 2015, 2017)*

- Mega-drought threat to **US Southwest** *(Nature, 2011)*

- Regional drought has a global impact on "Economy & Government" . (**Example: Russia &China**) *(Nature, 2011)*

- Millennium Drought (2001-2009) that affected **southeast Australia *(WRR, 2013).*** Possible worst drought ever.

- Severe drought has lasting effects on **Amazon *(Nature, 2012).***

Drought Definition

➢ More than <u>100 definitions</u> around the world. For example,

<u>United Kingdom:</u> 15 consecutive days or more (Rainfall< 0.008 inches)

<u>India</u>: seasonal rainfall < 75% of its long term average value

✓ A sustained, extended **<u>deficiency in precipitation</u>** (WMO, 1986)

✓ Percentage of years **<u>when crops fail</u>** from the lack of moisture (FAO, 1983)

✓ A significant **<u>deviation from the normal</u>** hydrologic conditions of an area (Palmer, 1965)

✓ A sustained period of time **<u>without significant rainfall</u>** (Linseley, 1959)

➢ **<u>Challenge:</u>** Differences among regions in terms of

• Hydro-meteorlogical variables, patterns, and spatio-temporal distribution

• Water supply vs. demand become an obstacle to having a precise definition of drought.

Quantification of Drought Events

Theory of run

$\longleftarrow$ D $\longrightarrow$

S

Months

D = duration, S=severity, I=intensity=S/D
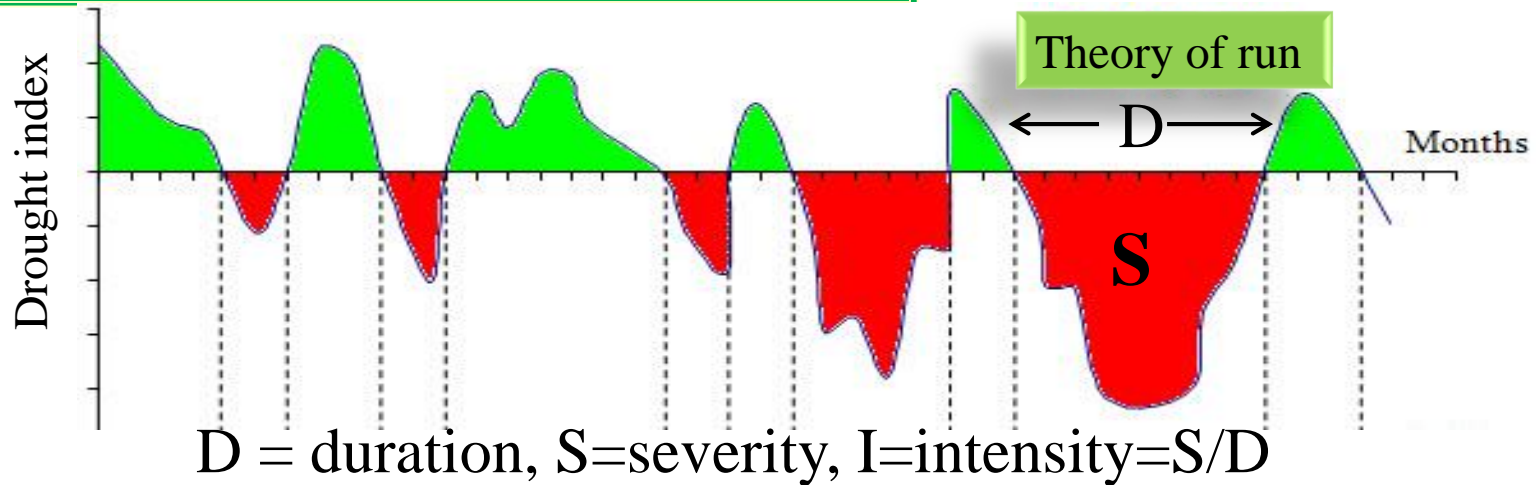
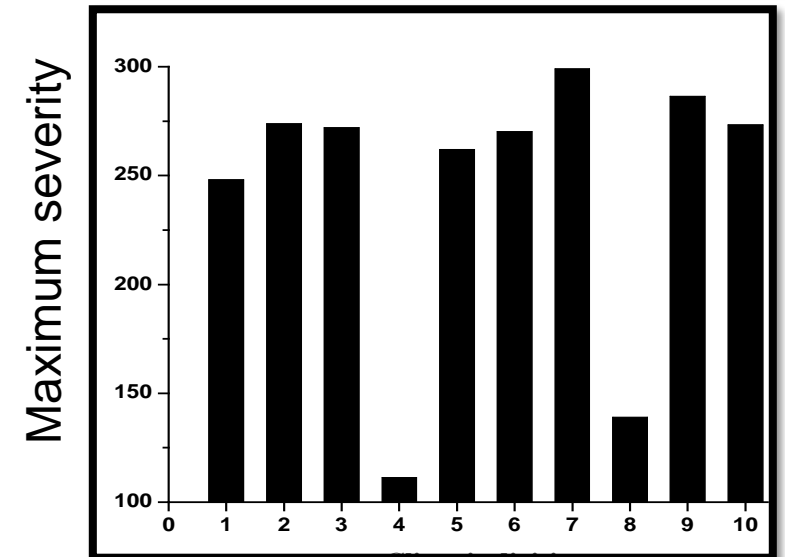❖ Standardized precipitation index (SPI)
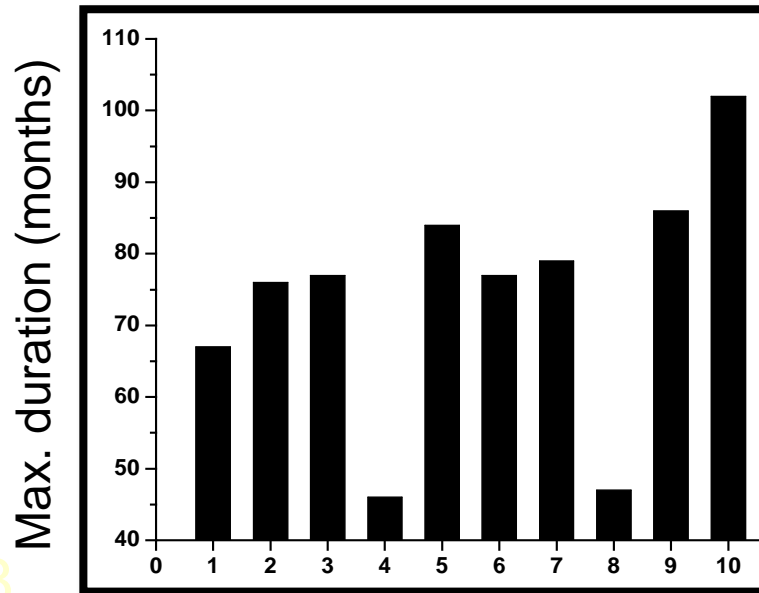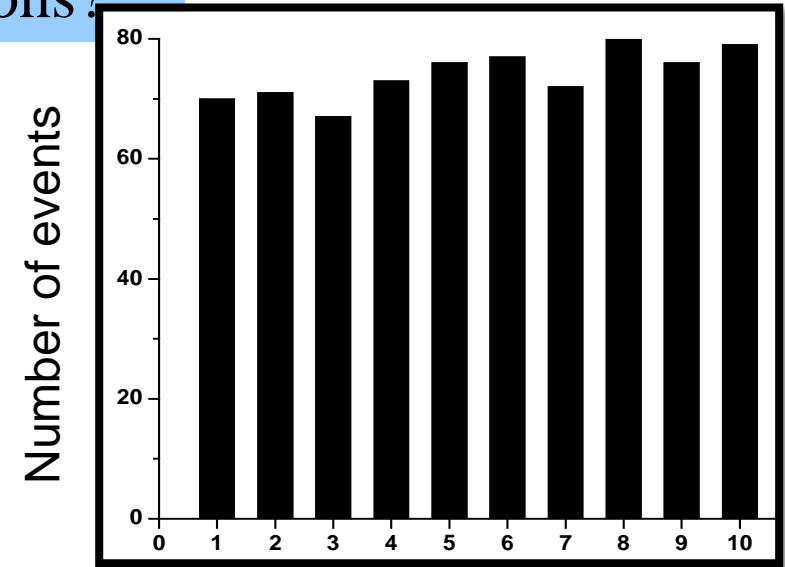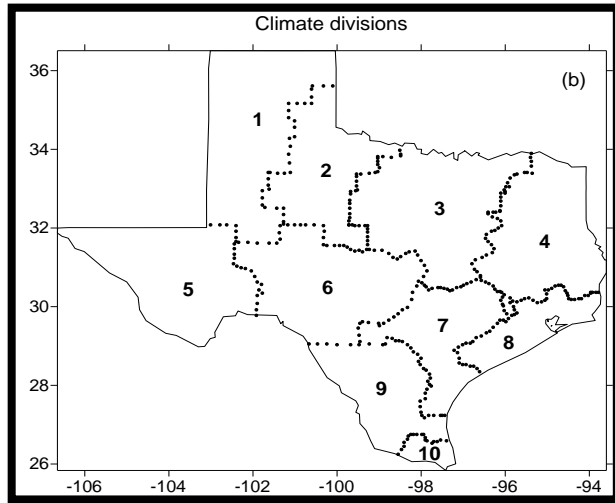
= f (precipitation)

❖ Palmer drought severity index (PDSI)

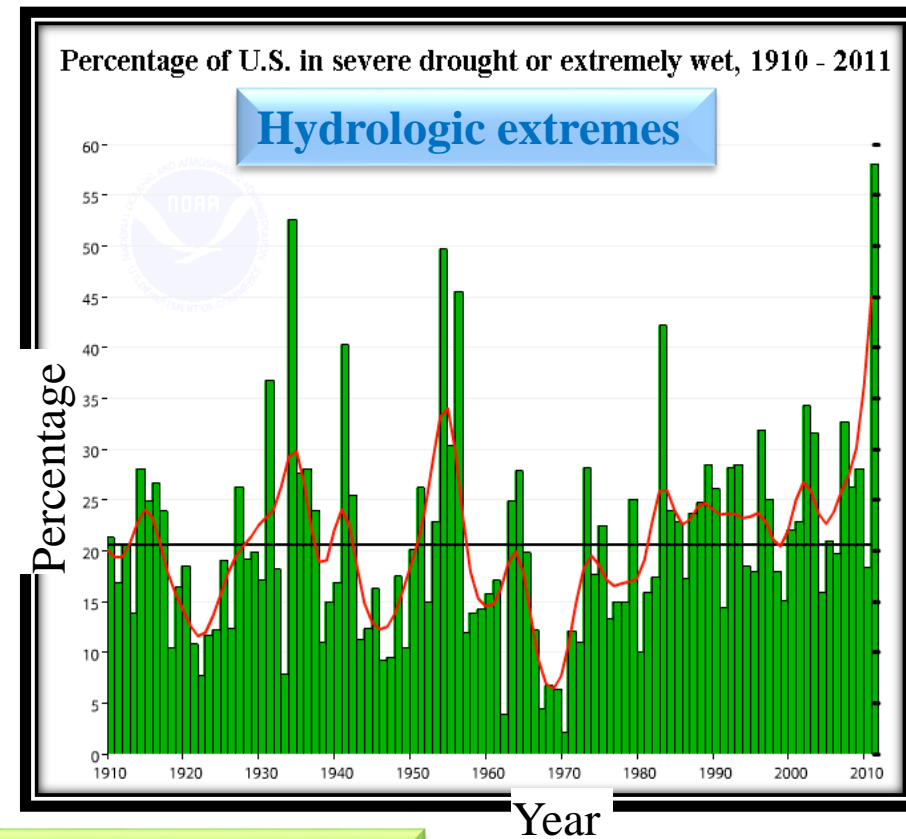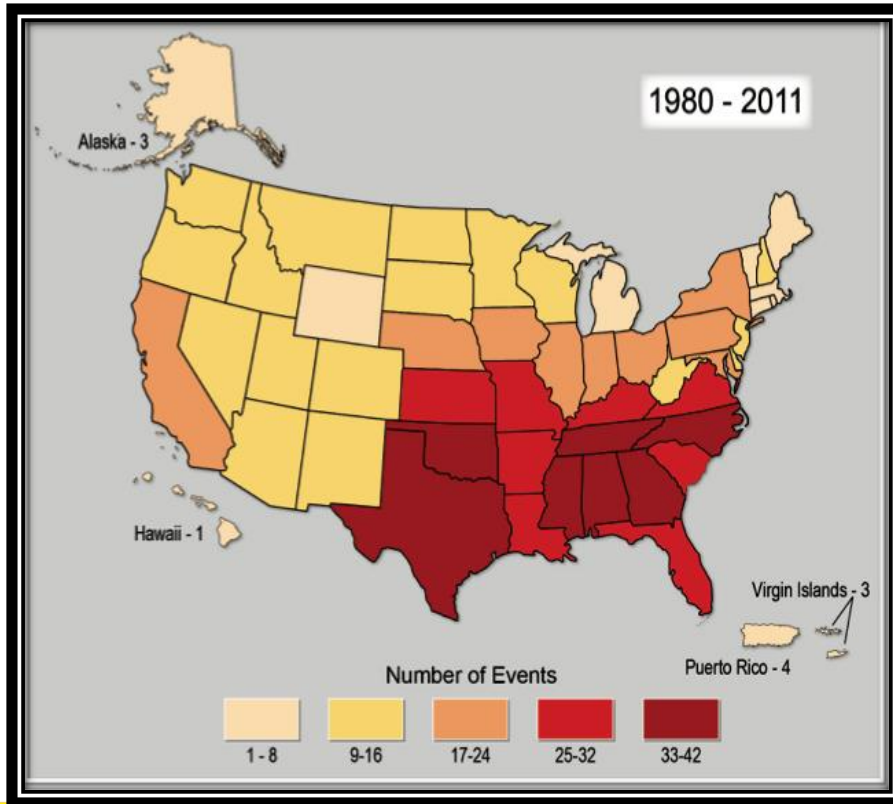= f (precipitation, temperature, soil moisture)

Drought Variability using PDSI

Does drought vary among climatic divisions?

X axis: Climatic division number

Billion Dollar Climate Disasters in USA

1980 - 2011

Alaska - 3

Hawaii - 1

Virgin Islands - 3

Puerto Rico - 4

Number of Events

1 - 8 | 9 -16 | 17 - 24 | 25 - 32 | 33 - 42

Percentage of U.S. in severe drought or extremely wet, 1910 - 2011

Hydrologic extremes

Percentage

Year

Dust bowl drought (1930's)

1980 drought
$ 56b
10,000 deaths

1988 drought
$ 72b
7,500 deaths

Hurricane Katrina
$ 134b
1,833 deaths

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Drought Indices (Overview)

Drought Indices	Input Variables				Advantages	Disadvantages
	P	T	R	Others		
SPI	√				Simplicity.	**Do not consider temperature**, PET, wind speed, and soil moisture data as an input variable.
PDSI	√	√	√	√	Evapotranspiration and soil moisture is also considered along with precipitation.	PDSI suffers from a considerable time lag **in identifying developing and diminishing droughts**. PDSI also inherits **a negative bias in runoff estimations** by assuming that runoff occurs only after all the soil layers are saturated.
CMI	√	√			It is comparable with different climate regimes	Highly sensitive to rapidly changing conditions. Recovery from long-term drought events may be falsely captured by CMI.
SPEI	√	√			It captures the combined effect of precipitation and PET.	Unlike the PDSI, the SPEI is not based on the water budget framework and **fails to incorporate the soil moisture component for identifying agricultural droughts**. In semi-arid regions, the SPEI may be **more sensitive towards the ET$_{ref}$**, while in humid regions, it shows **more sensitivity to precipitation.**
PHDI	√	√		√	It is based on a water balance approach that considers the total water system into consideration.	The impact of human influences is not considered in the calculations.
Multivariate Drought Index	Combination of any variables (for e.g., P, R, SM, R)				Capture multiple aspects of drought conditions for efficient drought monitoring and early warning.	It can be confusing to pin-point which type of drought is investigated. P=Precipitation, T=Temperature, R=Runoff, SM=Soil Moisture.

Classification and propagation of droughts
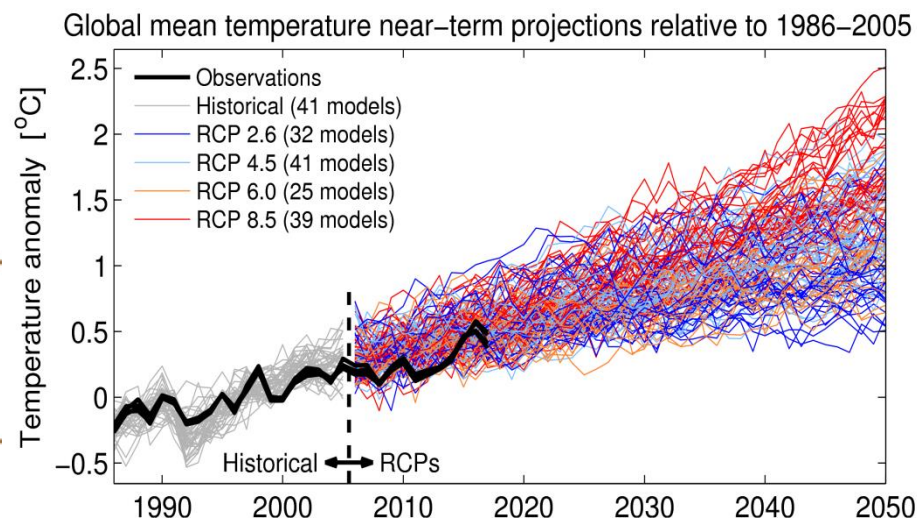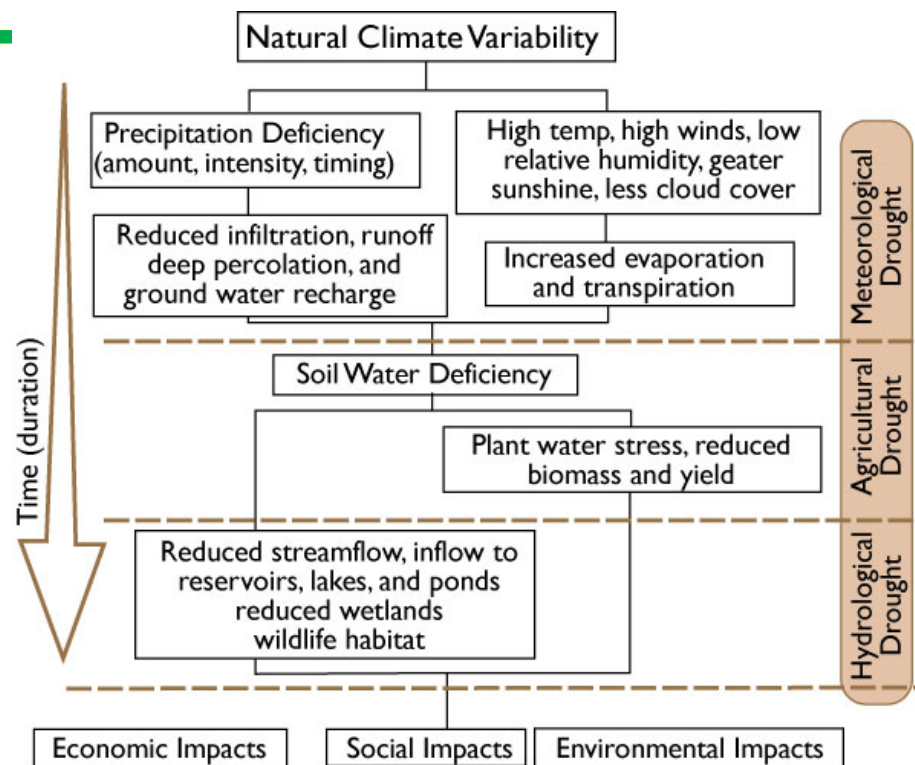
Updated version of IPCC AR5 Figure 11.25a, showing observations and the CMIP5 model projections relative to 1986-2005. The black lines represent observational datasets (HadCRUT4.5, Cowtan & Way, NASA GISTEMP, NOAA GlobalTemp, BEST). Source https://www.climate-lab-book.ac.uk/comparing-cmip5-observations/

Flow of drought:
Meteorological ⟶ Agricultural ⟶ Hydrological

❖ Highly non-linear process and involve feed-backs,
❖ Its impact propagates through multiple levels un-equally that often cannot be quantified objectively.

Association: Drought Indices & Land Surface Warming

Example of the Association Between Drought Indices & Land Surface Warming

Drought: The self-calibrated PDSI (PDSI_sc): precipitation, temperature, PET, and runoff.
Temperature: LSAT was obtained from the updated CRUTEM4 dataset (1850–2017) at 0.5° resolution.
Analysis period: 1975 – 2014 (a steady and sharp rise in global tropospheric temperature). **Baseline** period: 1961–1990
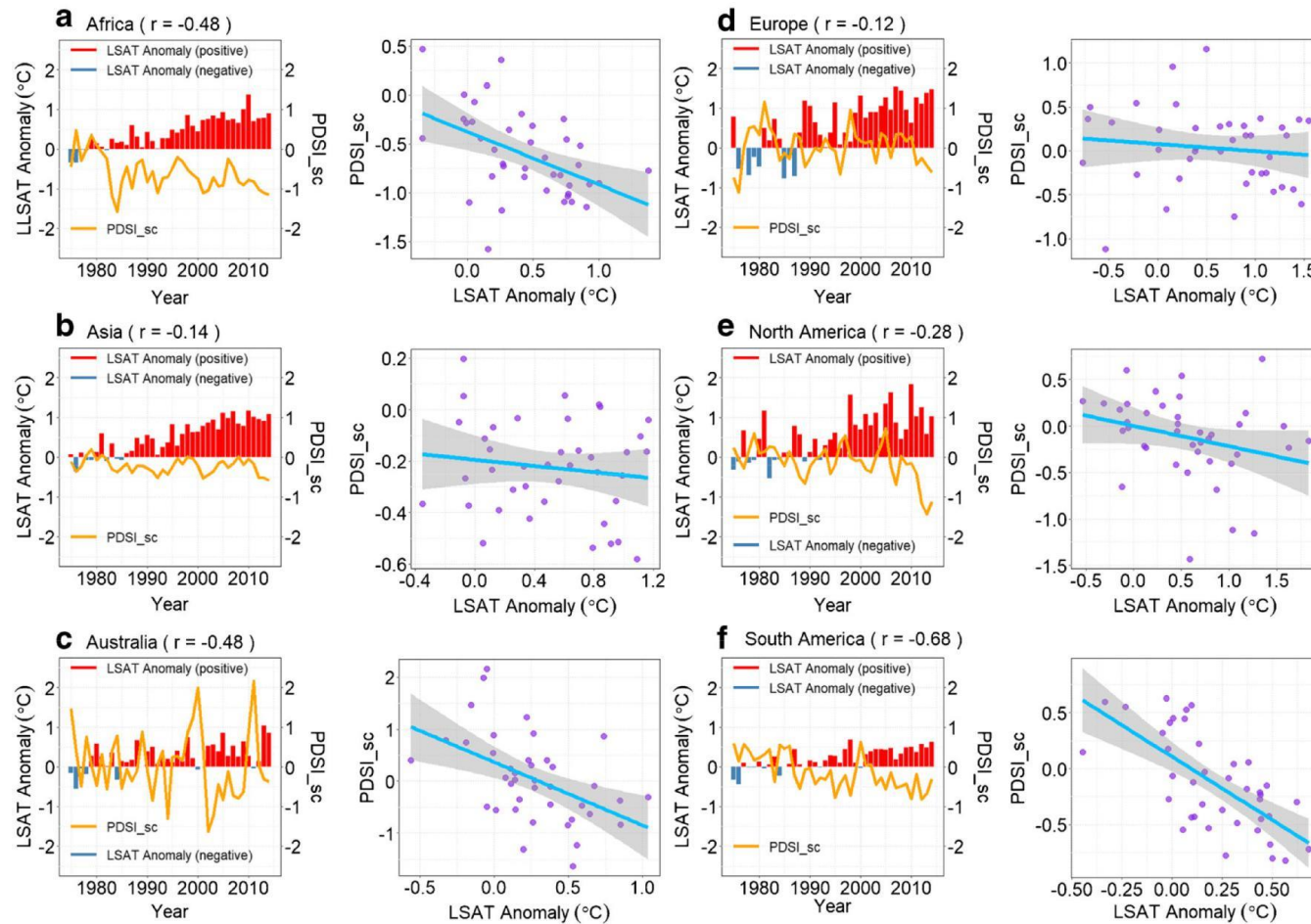
Stronger correlation
South America (− 0.68)
Africa (− 0.48),
Australia (− 0.48)

Relevance of Drought Indices in Climate Change

Climate change-induced warming **has accelerated water cycle**:
- ❖ Increasing the energy available for evapotranspiration (ET)
- ❖ Increasing the **temperatures** and thus the **water holding capacity** of the atmosphere.
- ❖ **Temperature** is likely to be **an important variable** for deriving appropriate drought indices under global warming.

Existing Limitations:
- ❖ Studies on **dryness often fails** to consider the background aridity.
- ❖ Drought indices **fail to incorporate the changes** in available energy, air humidity, and wind speed that may lead to a spurious increase in drought under warming climate.
- ❖ Therefore, it is important to consider the **factors that govern the background state**.

# Challenges: Drought Indices for Climate Change Studies

(1) Disagreement Among Drought Indices

Drought indices: SPI, SPEI, and PDSI_sc; Temporal window 1 month

Drought Indices	Comment
SPI 1	Data: Global Precipitation Climatology Centre (GPCC)
SPEI 1	Global SPEI dataset (http://spei.csic.es/database.html) PET: Penman-Monteith method
PDSI_sc	Data: https://www.esrl.noaa.gov/psd/data/gridded/data.pdsi.html

❖ A shorter temporal scale (e.g., SPI 1) can capture the influence of the warming on the loss of soil moisture leading to drying more effectively

❖ The global gridded datasets of SPI-1, SPEI-1, and PDSI_sc are spatially averaged to generate time series at monthly scale.

Sensitivity analysis: the magnitude of drought indices corresponding to every 0.25 °C change in global mean temperature [Range: − 0.5 to 0.75 °C].
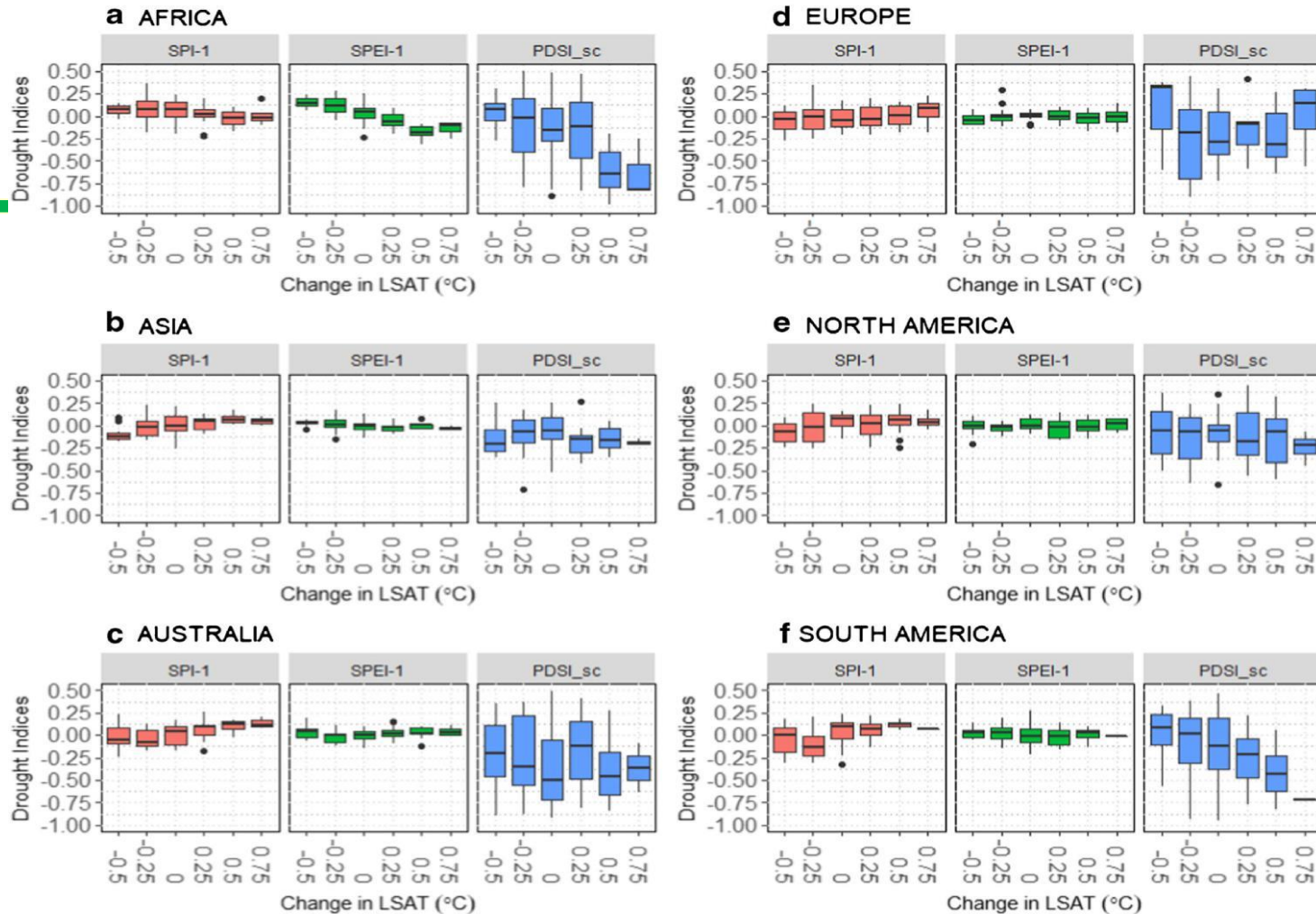
- ❖ Compared to PDSI_sc, SPI-1 and SPEI-1 show a little change with rise in warming
- ❖ SPI does not incorporate temperature or related variables as an input
- ❖ SPEI lacks the ability to produce comparable results between climate regimes
- ❖ PDSI_sc captures a consistent increase in drying with the rise in temperature
- ❖ **Limitations: (a)** one drought index responds to the long-term drying with rise in temperature, while two other indices behaved differently, (b) drought indices can arrive at different results that leads to ambiguity in the decision making.

(2) Sparse Availability of Precipitation Data

Sparse and poor quality of precipitation data generate **large uncertainties in quantifying spatio-temporal drought** assessment under climate change.

❖ Distributions of rain gauges used for July 2005 in the data sets CPC, GPCC, CRU, and PRECL, respectively.
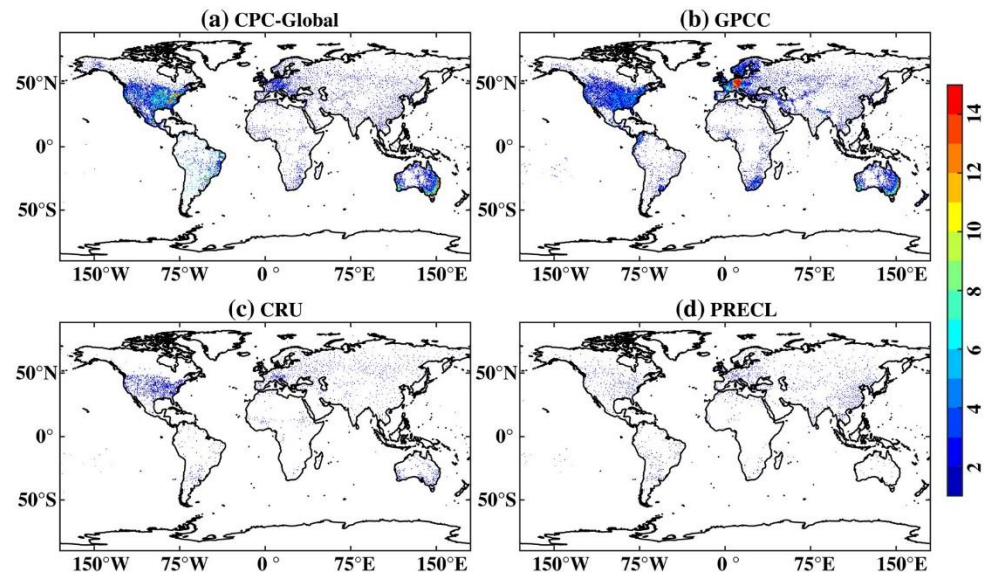
❖ There is a **decreasing pattern in number of rain gages** over the years.
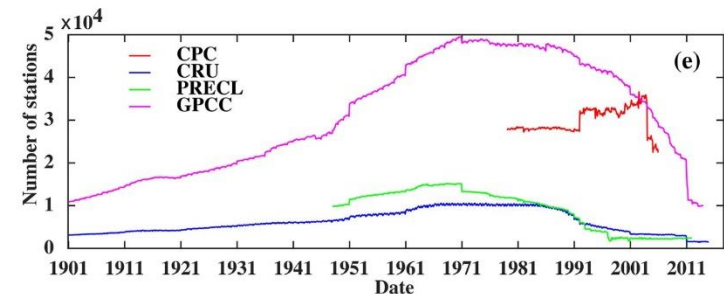
(3) Estimation of PET

- ❖ PET refers to the atmospheric evaporative demand
- ❖ Extensively used in drought studies
- ❖ Important variable in the estimation of **PDSI, RDI, and SPEI.**
- ❖ Robust estimation of PET is crucial in the reliable assessment of drying under the changing climate.

Thornthwaite (TH) equation

$$PET = 16\left(\frac{L}{12}\right)\left(\frac{N}{30}\right)\left(\frac{10T_a}{I}\right)^{\alpha}$$

$$\alpha = (6.75 \times 10^{-7})I^3 - (7.71 \times 10^{-5})I^2 + (1.792 \times 10^{-2})I + 0.49239$$

$$I = \sum_{i=1}^{12}\left(\frac{T_{ai}}{5}\right)^{1.514}$$

Penman–Monteith (PM) equation

$$\lambda_v E = \frac{\Delta(R_n - G) + \rho_a c_p(\delta e)g_a}{\Delta + \gamma(1 + g_a / g_s)} = Energy\ flux\ rate.$$

$$ET_0 = \frac{\lambda_v E}{L_v} = Volume\ flux\ rate.$$

TH method: Temperature based : Likely to overestimate drying under warming scenarios (116).

PM method: found to be more robust in the estimation of PET compared to other existing methods (It includes additional climate variables, such as, radiation, wind speed, vapor pressure deficit, and humidity)

- ❖ **Example:** Milly and Dunne reported discrepancies in the estimation of the change in PET that leads to bias in continental drying trends

(4) Downscaling of Meteorological Variables

- ❖ **<u>Challenge:</u>** **Higher uncertainty** is associated with precipitation in terms of its spatio-temporal distribution.
- ❖ The downscaling techniques **performs poorly for precipitation** compared to temperature
- ❖ Drought indices (e.g., SPI) solely derived from precipitation **may not be a right indicator** for drought assessment under climate change.

- ❖ **Drought assessments using GCM outputs are limited:** (a) higher bias associated with the precipitation estimates, (b) substantial intrinsic uncertainties originating from the inter-model variability.

- ❖ **GCMs do not exhibit a high degree of predictability** especially over the **extra-tropics** owing to the limited physical understanding of the ocean-atmosphere inter-actions in those regions.
- ❑ This sets a major limitation to specify initial conditions for meteorological drought prediction.

(5) Choice of Baseline Period

The **choice of baseline period plays an important role** when comparing future drought under climate change with respect to historical drought as the reference period.

<u>Longer base period:</u>

❖ By selecting a longer base period, the drought indices can be better calibrated.

❖ In ideal scenarios, **baseline climatology that captures historical major drought events**, Dust Bowl: the dry 1930s (1930–1931, 1934, 1936, and 1939– 1940) is likely to yield a different set of results.

❖ The selection of 1950–2008 as the baseline period may include the **effects of recent anthro-pogenic climate change** that may be responsible to mask the climate change signals in the results of the analysis.

❖ Choice of different baseline periods can generate discrepancies in summarizing the results **related to the same drought episode**.

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(6) Non-stationary Climate
(Choice of Probability Distribution)

❖ The **appropriate selection of probability distribution** plays an important role in deriving robust drought indices.

❖ The probability distribution **parameters will change over time** especially considering stationary (historical) vs. non-stationary (future scenarios) patterns of climate variables.

❖ Drought characteristics (e.g., severity, duration and frequency) will be different between stationary and non-stationary climate.

❖ Therefore, it is **important to consider non-stationarity** by changing the probability distribution parameters over different timescales to improve drought assessment under climate change.

(7) Defining the Role of Anthropogenic Influence

❖ Apart from the natural variability of climate, **human activities have a significant control on drought** initiation, propagation, and societal impacts.

❖ Human-made infrastructures, such as dams and reservoirs, can also greatly affect the **propagation of soil moisture and hydrological drought**.

❖ Drought indices **needs to capture such changes in drought propagation** along with other human interactions such as dynamic changes associated with land use, irrigation efficiency, and rapid increase of population.

❖ However, dynamics of human interactions is still in a preliminary stage in existing large-scale hydrologic modeling framework, and scientific advances are needed to overcome these challenges.

Meaningful Applications of Regional Drought Indices

Objective

- Drought index is calculated at coarser resolution

- Coarse resolution: Low variability, no downscaling and bias correction.

- Can be useful for climate change assessment

- **Drought Indices Performance was evaluated with respect to**:

✓Streamflow

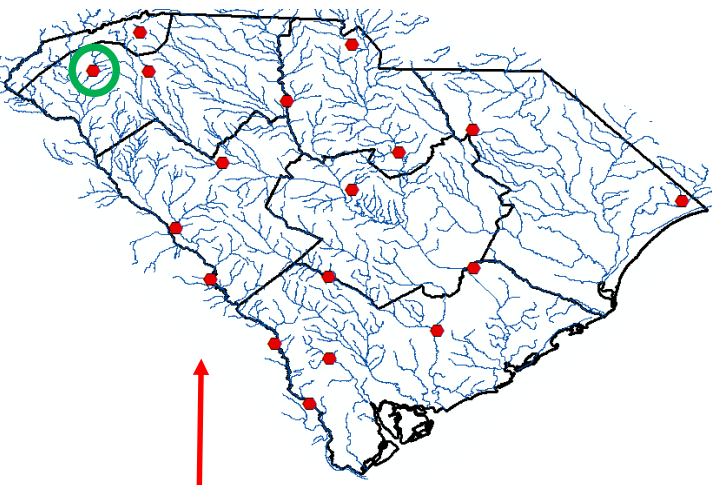✓Reservoir level

✓Soil moisture

✓Crop yield (Corn, Soybean)

Study Area

Observed drought trends, 1958 - 2007

PDSI

Increasing drought   Decreasing drought

[Reference: Eco-west, http://www.slideshare.net/ecowest/water-in-the-american-west]

SC Climate divisions
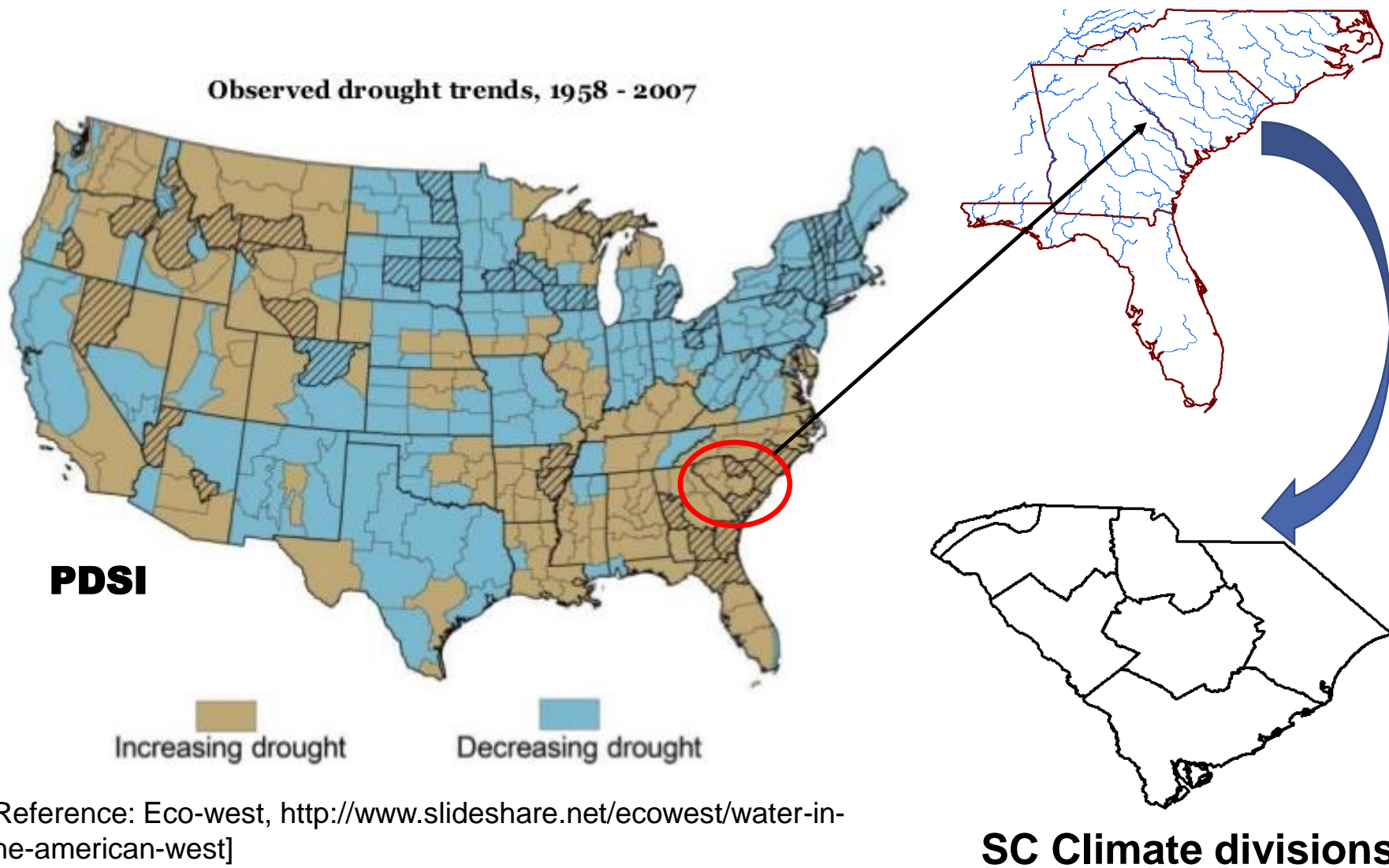
Drought indices used

Drought Index	Comments
The Palmer Drought Severity Index (PDSI)	Precipitation, Temperature and Available soil water content
Palmer hydrological drought index (PHDI)	Derived from PDSI to quantify the long-term impact of drought
Palmer Z index (ZNDX)	Detection of short term drought
PMDI	
Standardized Precipitation Index (SPI)	Precipitation

Boxplot showing the correlation of streamflow with drought indices

The locations of streamflow gages included in the analysis
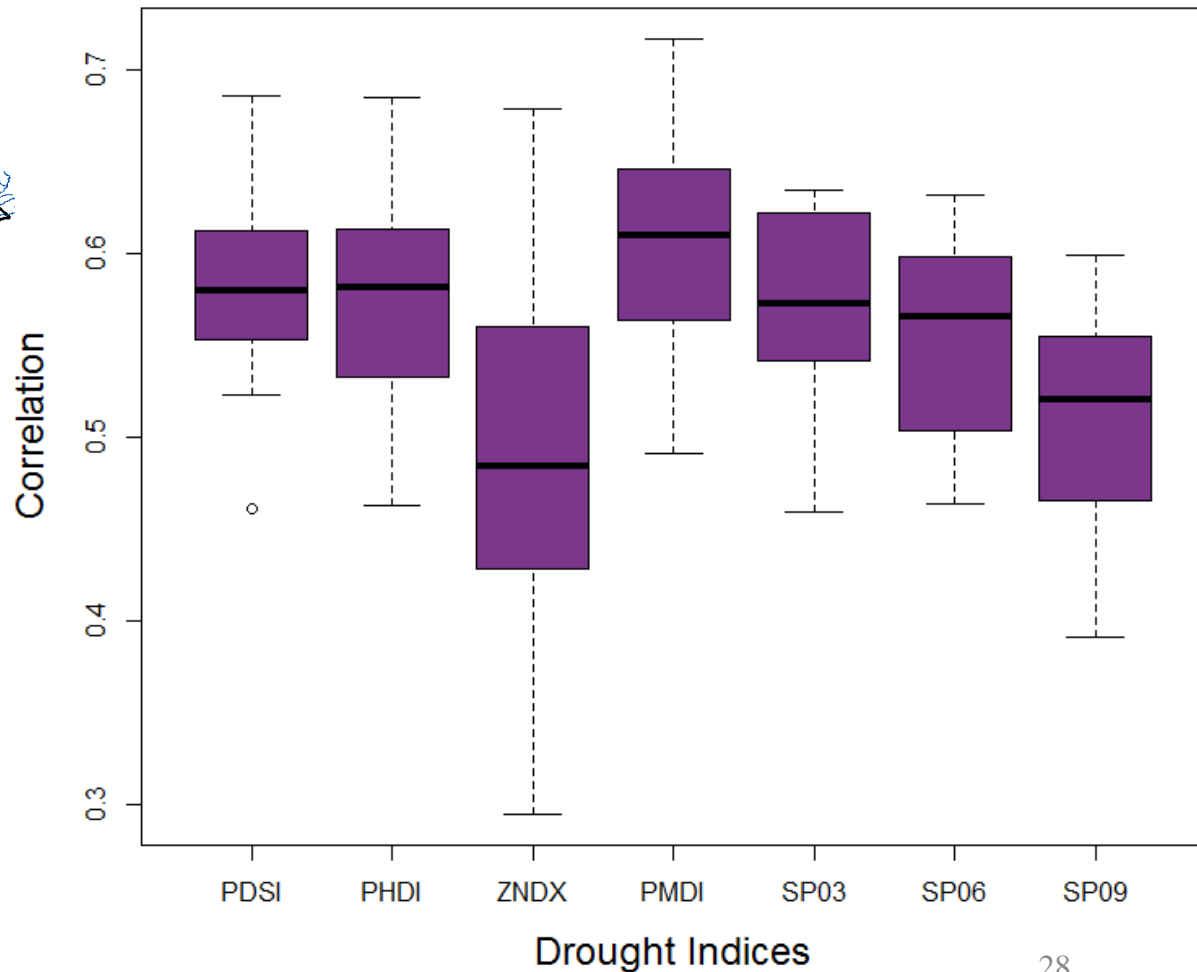
PDSI & stream flow

Gage location:- USGS 02186000
Twelve mile creek near liberty
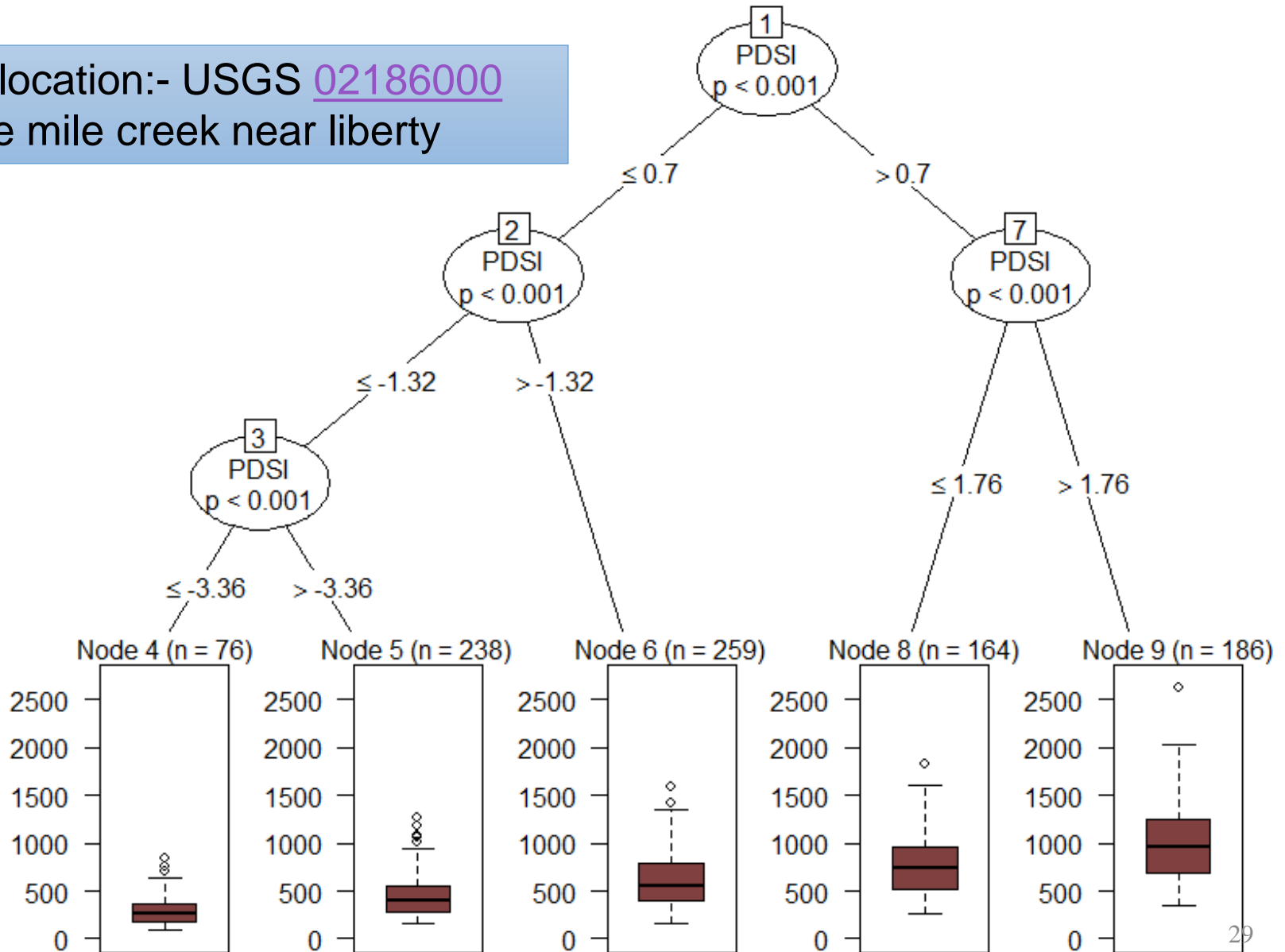
SPI 3 & stream flow

Gage location:- USGS 02186000
Twelvemile creek near liberty
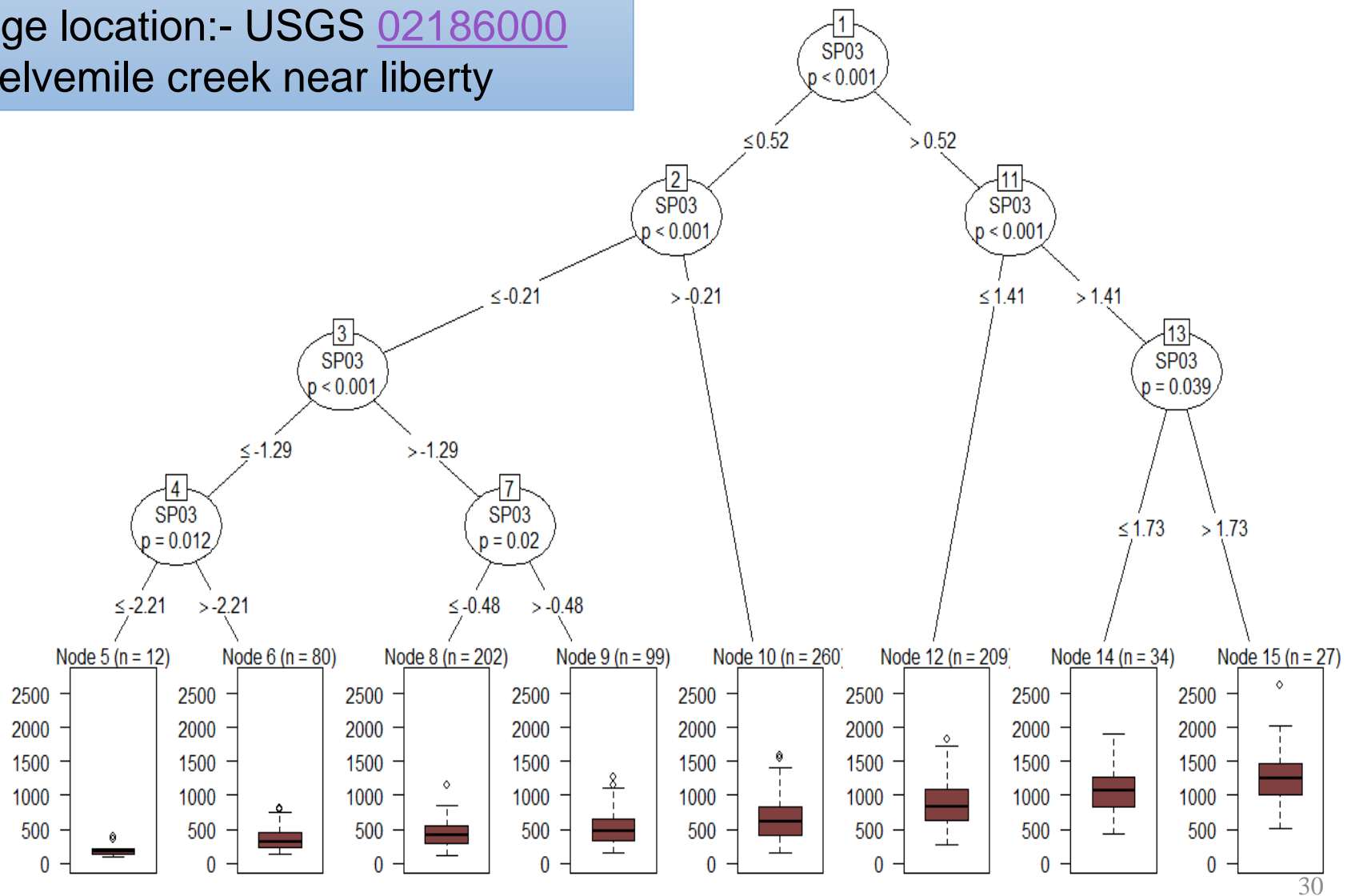
Correlation: Reservoir level with drought indices
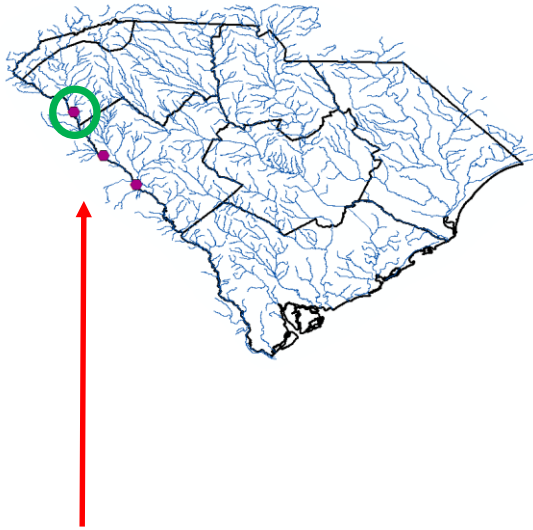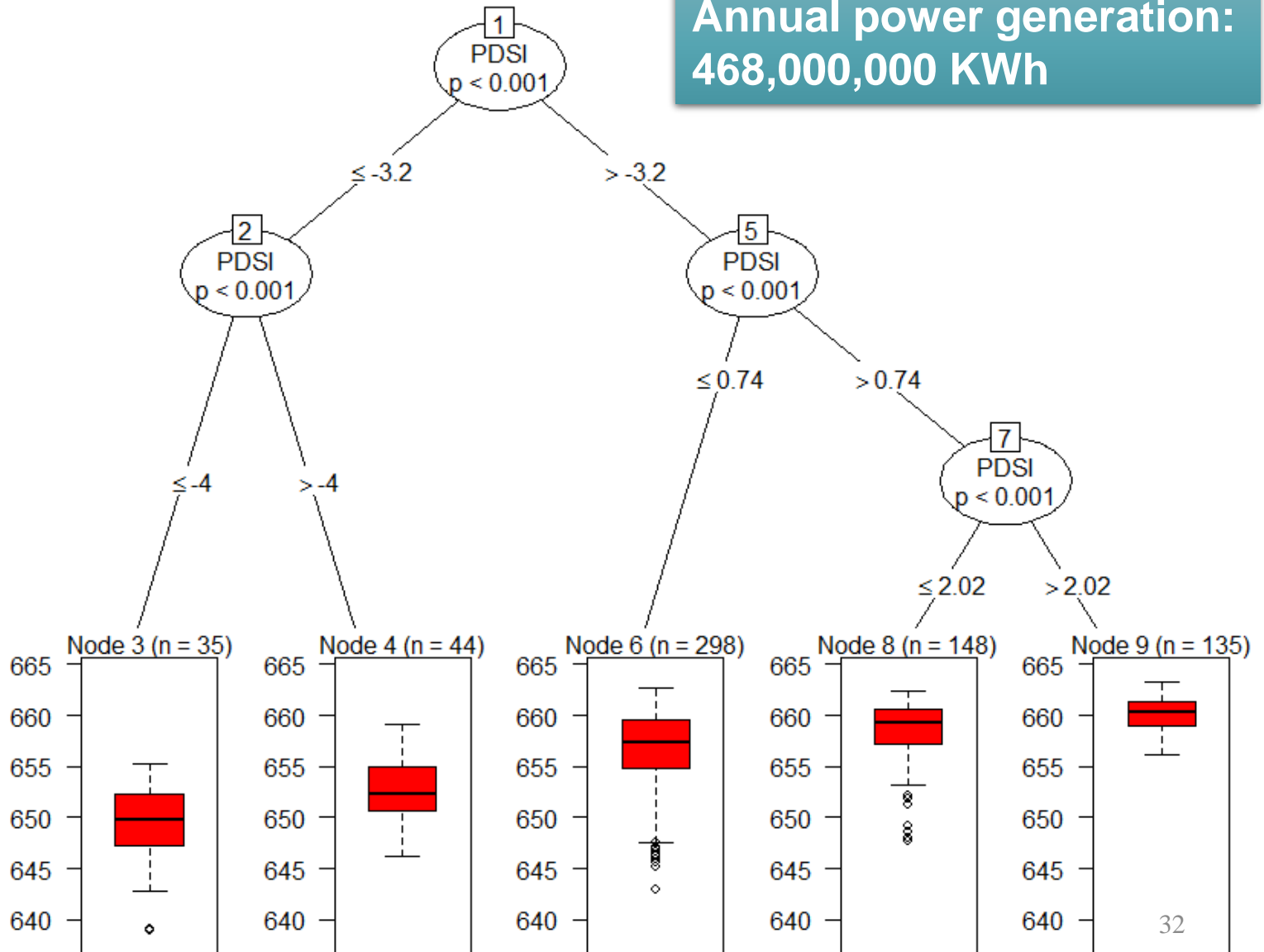

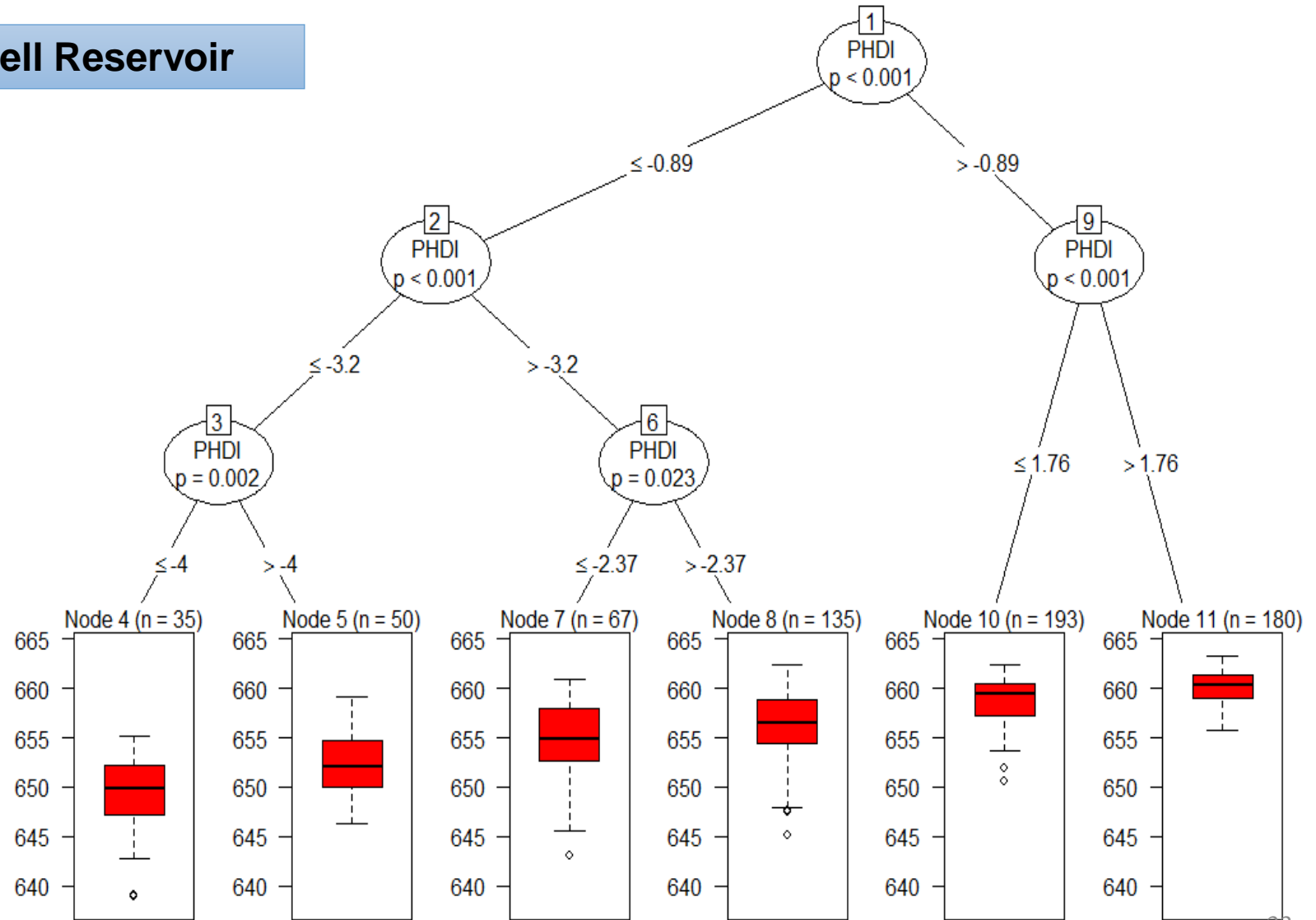The locations of reservoirs included in the analysis
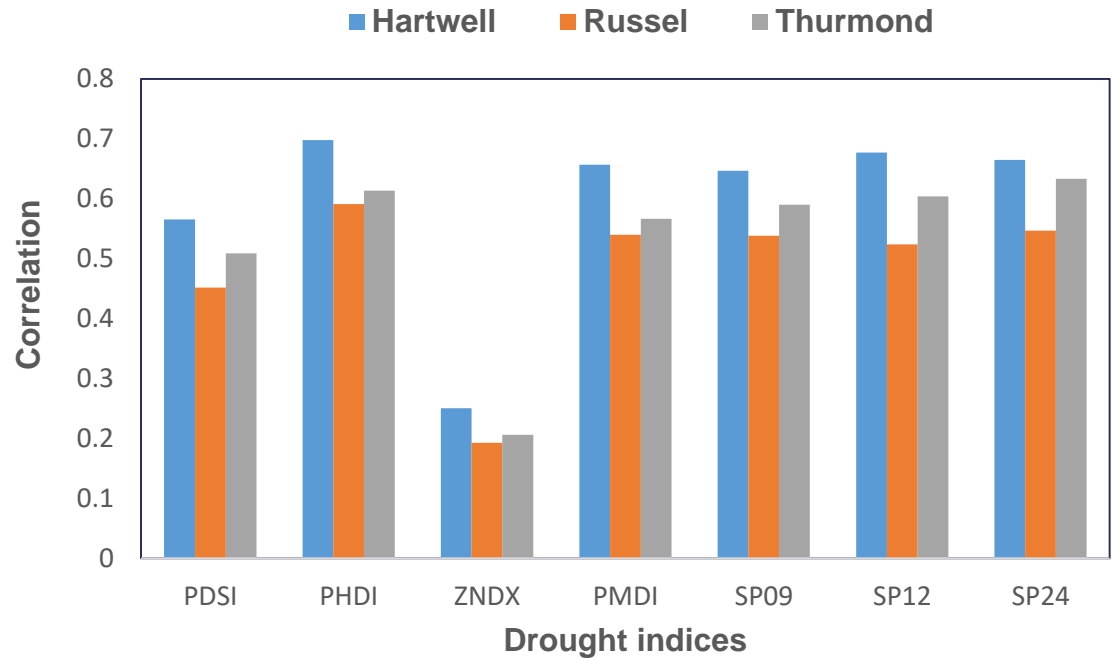
PDSI & Reservoir Level

Annual power generation: 468,000,000 KWh
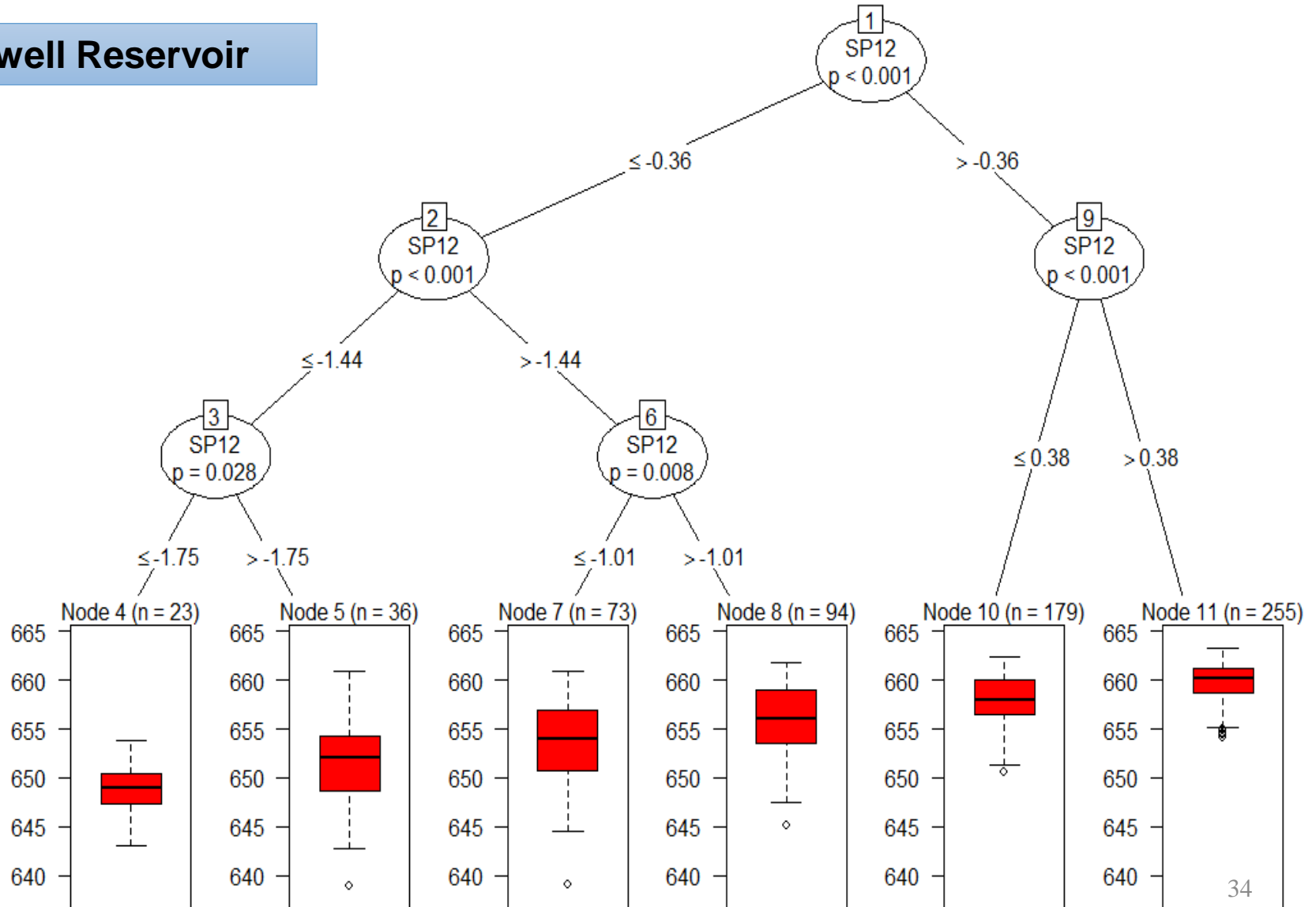
Hartwell Reservoir

Drainage area: 5409km²
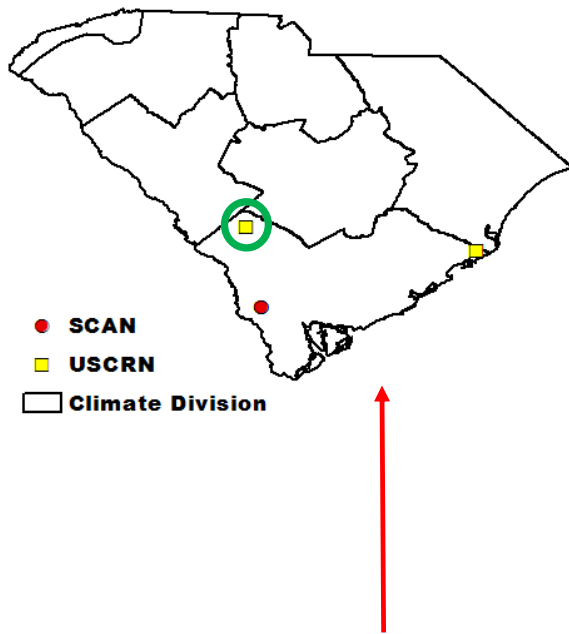
PHDI & Reservoir Level

Hartwell Reservoir
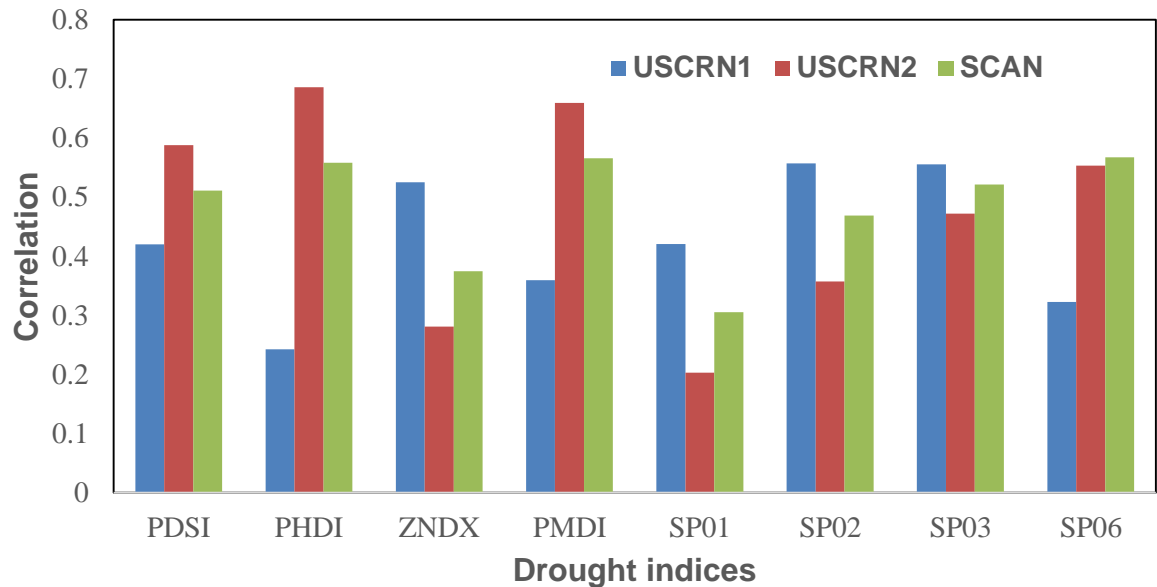
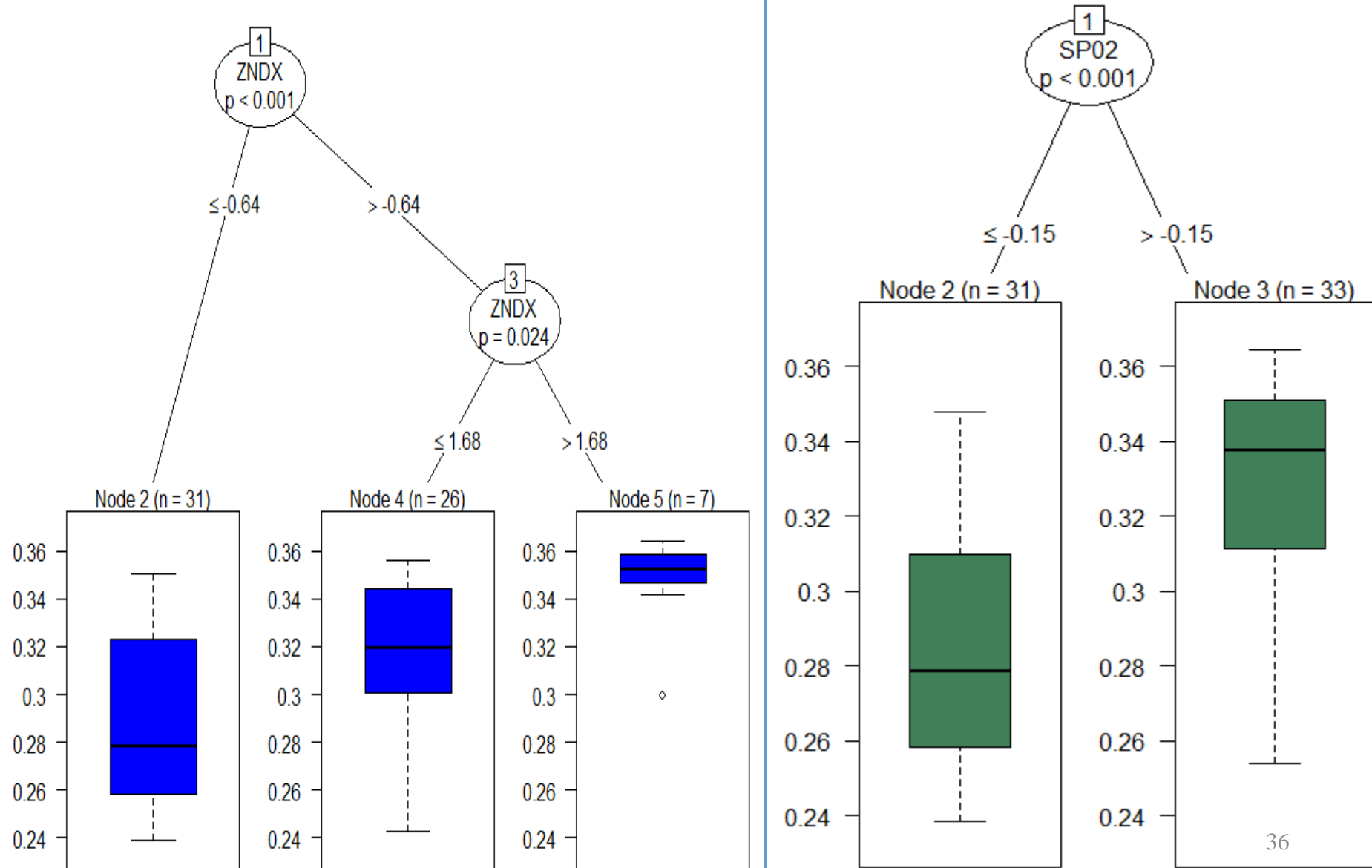# SP12 & Reservoir Level

Hartwell Reservoir

Correlation of soil moisture with drought indices

The locations of soil moisture stations included in the analysis

ZNDX (SPI 2) & soil moisture content at the depth of 100 cm

Summary and Conclusions (Key points)

❖ Formulation of drought indices without considering the **factors that govern the background state** may lead to drought artifacts under a warming climate.

❖ Estimation of **PET based on the energy budget framework** can be a better physically based approach compared to only temperature-based equations for drought assessment.

❖ Separating the natural causes from the human-induced factors is most likely to make drought assessment more realistic. This can be achieved by objectively **defining the role of human activity in deriving drought indices**.

❖ Climate change **affects a wider range of interconnected sectors**, thereby further **increasing the inherent complexity** of quantifying socioeconomic droughts

❖ Improved downscaling approaches should be developed to transform the **information from coarser resolution to finer grid cells**. Limitations in downscaling methods can be referred to Maraun et al.

❖ The **non-stationarity associated with climate change** is likely to alter the parameters of the probability distributions of input variables in the formulation of drought indices.

❖ Therefore, adopting appropriate methods **to capture non-stationary information for characterizing drought** under climate change will likely to generate reliable information for risk assessment

Thank You !